Novel Technologies of Exoskeleton Systems Applied to Rehabilitation for Hand Therapies: A Technological Review

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Abstract— Movement disorders and injuries affect partial or full control of the parts of the body that affect your movement. Among the affected parts are the hands, which are vital to carrying out daily activities. According to the World Health Organization (WHO) around 15% of the world's population, that is, 1000 million people, suffers from some type of disability. Only in Peru, there are around 1 million 575 thousand people who suffer from a variety of deficiencies, according to the National Institute of Statistics and Informatics (INEI). As a solution to this problem, hand exoskeletons emerge, which are devices that restore or improve the motor skills of the affected hand. In this review, 64 publications on hand exoskeletons were analyzed and classified into the following categories: trade names, acronyms or the name of the main author of the device, the degrees of freedom, the type of exoskeleton that can be passive or active, the mechanism that covers the parts of the hand, the types of movements that are performed, the kind of rehabilitation, the pathology that causes the injury or disability in the hand and the technology readiness level.

Keywords—Hand, exoskeletons, rehabilitation, finger, wrist, biomechatronic

I. INTRODUCTION

According to the World Health Organization (WHO) around 15% of the world's population, almost one billion people, suffers from some type of disability [1]. Motor disability is characterized by damage to the musculoskeletal system. Movement disorders and injuries that affect partial or complete control of the movement of body parts. Nowadays, one of the most serious problems is the loss of control of the hands since they are essential to carry out daily activities. Disability can be caused by different factors. Among them are neurological disorders, which, according to the Pan American Health Organization (PAHO), have been a public health challenge since the year 2000 [2]. Likewise, a 2007 United Nations report describes that approximately one in six people in the world suffers from these disorders [3]. And, by 2022, the third leading cause of death and disability combined was cerebrovascular accident (CVA) according to the World Stroke Organization (WSO) [4]. By comparison, in Latin America and the Caribbean, it is estimated that approximately 66 million people suffer from a disability [5]. While in Peru, the National Institute of Statistics and Informatics, announced that about 1 million 575 thousand people suffer from some type of disability. Of which motor disability stands out as the most common, affecting around 932 thousand people [6].

Loss of motor skills can be caused by multiple factors, which can be divided into four types: congenital, hereditary, perinatal, and acquired in the postnatal stage. First, congenital causes include conditions acquired during pregnancy, such as congenital malformations. Secondly, hereditary causes are those that are transmitted by DNA from parents to children [7]. Among them are some neurodegenerative diseases. Thirdly, within the perinatal triggers of a motor disability, that is, at the time of delivery, are the prolonged lack of oxygen or obstruction due to accidents with the umbilical cord [8]. Lastly, the causes acquired in the postnatal stage include from birth to death of the human being. These include strokes, injuries such as trauma or spinal cord injuries, mobility problems such as muscle disorders, quadriplegia/tetraplegia or hemiparesis/hemiplegia, and neurological disorders such as spasticity. Consequently, people with disabilities have difficulties developing, interacting in society and performing daily activities. This is because their environment has a significant influence on their experience, development, and the degree of disability [9]. In particular, the barriers they face include inaccessible facilities and tools, increased risk of health problems, discrimination, and socioeconomic disadvantages for efficient participation and full development.

Various devices have been developed to improve and reinforce motor skills of the hand, with exoskeletons being a promising solution for rehabilitation practices. The purpose of these devices is to progressively restore movement to the affected hand. Exoskeletons work by improving the activity of the hands in everyday tasks or by providing repetitive movements for neuromuscular re-education. The growing interest in the field of "Rehabilitation Robots" has led to the search for alternative solutions and different technologies to improve therapy. One approach is robot-assisted therapy, which is recognized as a viable adjunct to rehabilitation. Since it allows precise visual and mechanical control of the interaction with the user, which makes it an ideal tool for sensorimotor training [10]. This has the potential to effectively alleviate labor-intensive rehabilitation procedures and medical personnel [11]. Likewise, it allows improving traditional rehabilitation such as occupational therapy and neurorehabilitation. On the other hand, telerehabilitation implements the internet and telecommunications to improve exercises and therapeutic training. Therefore, this review will describe and analyze the hand exoskeletons for rehabilitation that have appeared in the 64 publications as well as their various features in the evolution of the biomechanical movement, their different rehabilitation techniques, and the diversity of their applications in different pathologies.

II. Types of Rehabilitation

Rehabilitation is a crucial component of medical care that aims to improve the functioning and independence of patients. It is a complex process that involves restoring lost or diminished abilities of those who have injuries, illnesses or disabilities that have affected their competence to execute daily activities. Among the areas that are being explored to improve rehabilitation is robotics, the interest in this field lies in the ability to precisely control and reproduce movements, as well as the possibility to integrate with new technologies [12]. In general, rehabilitation requires a multidisciplinary approach, and hand rehabilitation is no exception. Therefore, there are different types of rehabilitation to suit the specific needs of the individual. Among them, three types of rehabilitation stand out: Neurorehabilitation (NR), Telerehabilitation (TR), and Occupational Rehabilitation (OR). These types of rehabilitation are shown in Fig. 1.

B. *Telerehabilitation (TR)*

Telerehabilitation (TR) implements information and communication technologies (ICT), allowing improved human-machine interaction and enabling rehabilitation at home or in virtual environments. It has been applied in a range of contexts, including at home and medical facilities. The monitoring of therapies through applications or interfaces is increasingly accurate thanks to the use of sensors and remote monitoring technologies [19]. Thus, experts can continually customize and design exercise programs [20]. Likewise, the implementation of Artificial Intelligence (AI) and interfaces allow for improvement in the reading of biosignals and feedback. In addition, various platforms, applications, interfaces, and games have been created to make therapies more entertaining and constant. In that sense, virtual reality (VR) allows interaction with specific settings and environments designed for rehabilitation in real-time, which provides a more receptive response [21].

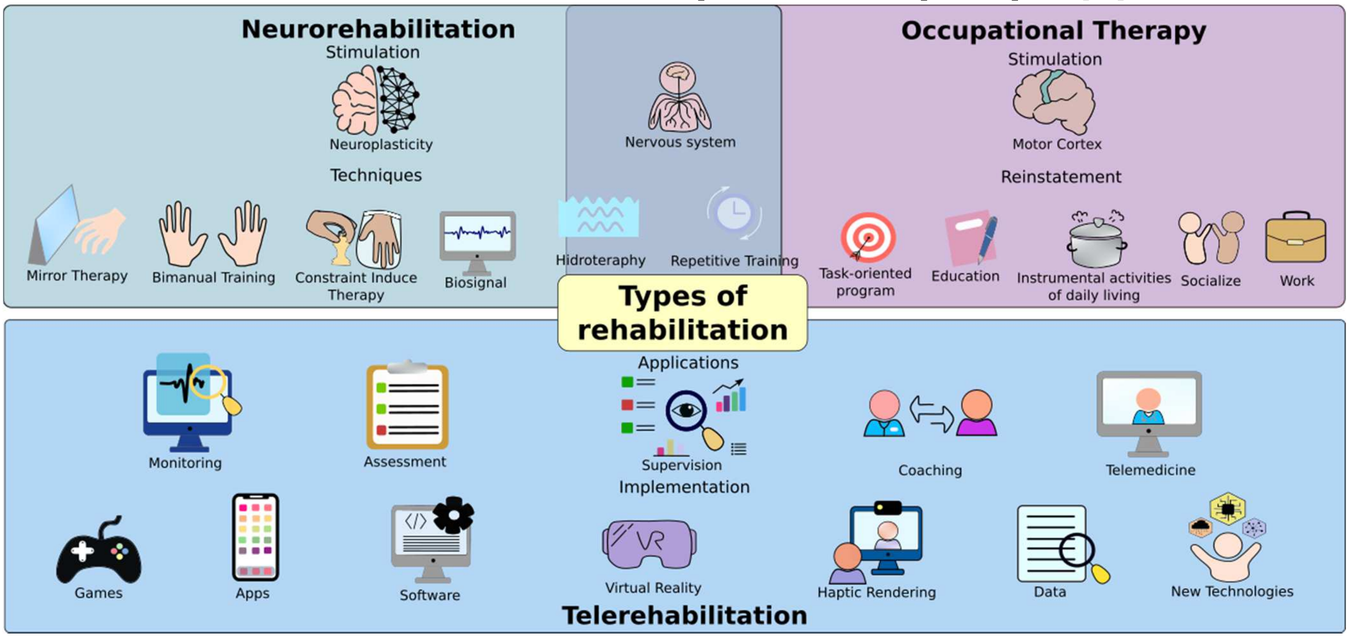

Fig.1. Rehabilitation Types

A. *Neurorehabilitation (NR)*

Neurorehabilitation (NR) aims to raise the standard of living for those who have endured various kinds of trauma or neurological disorders, for which a wide range of techniques and treatment approaches are implemented. For example, mirror therapy is one of many techniques that take advantage of the brain's neuroplasticity [13]. Techniques like bilateral training focuses on the coordination of both limbs [14] [15]. In the case of robotics, the exoskeleton of the arm is used to simulate the movement of the healed hand over the injured hand at the same time [16]. From the "learn-don't use" approach, Constraint Induced Movement Therapy (CIMT) has as its main components intensive repetitive exercise therapy for the affected part while restraining the less affected part, the application of various behavioral techniques and transfer from the clinic environment in the real world [17]. While the biofeedback aim is to facilitate teaching the patient about manipulation of involuntary events through visual and auditory signals of their internal physiological events, thus modulating cortical activity of the brain [18].

C. *Occupational Rehabilitation (OR)*

Occupational rehabilitation (OR) helps to improve motor function so that the patient can perform basic activities; thus, recovering their functional independence and preventing disability [22]. OR encompasses the adaptation of tasks or environments focused on increasing independence and quality of life [23]. OR includes the practice of specific tasks as one of its techniques, which consists of the repetition of a functional task to provide opportunities for the nervous system to integrate the position of the body; generating regular and progressive motor orders that ultimately end up with a motor output based on sensory feedback. All this is grounded by the fact that experience can shape the plasticity of the motor cortex [24]. The goal is to promote motor skills by regulating force, position, speed, and coordination. In addition, OR also encompasses activities of daily living training (ADLT). The ADLT seeks to restore the patient's ability to perform basic and instrumental activities, so it focuses on restoring balance or teaching the individual how to improve their functional abilities through adaptive devices.

III. Hand Rehabilitation Exoskeletons

Hand exoskeletons aim to improve the comfort level of the patient for which they can implement designs that allow rehabilitation. Mainly, robot-assisted rehabilitation is a method that includes repetitive training, the performance of specific movements passively or actively, the progressive increase in resistance, and the implementation of virtual environments for therapy oriented to the practice of daily life tasks [25]. Rehabilitation-targeted hand exoskeletons are devices that can restore or improve hand Ranges of Motion (ROM) as well as motor functions [26]. These can have several differences depending on their design, but generally they meet certain requirements such as being rightly integrated into the hand, guaranteeing a certain level of safety and comfort, and effectiveness in force transmission [25]. On the contrary, they can commonly be differentiated according to the following characteristics: objective, type of control, generated movements, biomechanics, and movement transmission mechanisms. These devices are typically used in clinical settings, but if their design allows for easy deployment and portability, they can also be deployed in any non-medical setting, such as the home. The effectiveness of exoskeletons largely depends on the biodesign of the machine, the interaction of the device with the person, the training method chosen or required by the patient, the range of control parameters, and the condition or pathology of the patient [26]. That being said, Table 1 is assembled from the review and ranking of 64 sources of hand exoskeleton intended for rehabilitation. The classification was given through 8 categories. First, the name that refers to the trade name or acronyms. In case of not having one that distinguishes it from other devices, the name of the main author of the device is used. Second, the degrees of freedom, which are parameters that indicate the number of movements that the exoskeleton can perform through three-dimensional space independently. Third is the type of exoskeleton, which can be passive or active depending on how it works and how it controls movement. Active exoskeletons use pneumatic or electric actuators and motors to generate movement, while passive exoskeletons do not have an external power supply. Instead, they use the energy generated by the user's own movements, storing and distributing it. Fourth, it refers to the mechanism of the exoskeleton that is designed to act on a certain part of the body. Fifth, the types of body movements that the device can induce. Like flexion and extension when the angle of the joint is reduced or increased respectively. Or abduction and adduction when moving away from or near the center line of the body respectively. Sixth, the type of rehabilitation. Seventh, the pathology that causes the injury or disability in the hand. Eighth, the Technology Readiness Level (TRL) as explained by the NASA. The methodology used to develop the table consisted primarily of searching for information using keywords on hand exoskeletons in databases such as the NCBI, Elsevier, Frontiers, IEEE, among other sources of information from the biomedical, biotechnology, and robotics literature. Likewise, the information was leaked, having exoskeletons intended for rehabilitation as requirements and limiting the years of publication of the articles in the range of 2019 to 2023.

TABLE I. Exoskeletons for Hand Rehabilitation

Name / Ref.	DOF	Type	Mechanism	Movement	Rehab	Pathologies	TRL
Xia *et al.* [27]	13	A	F	F/E, I/E	TR	Stroke	8
Yang *et al.* [28]	5	A	F	F/E	TR, NR	Impaired Mobility	5
Singh *et al.* [29]	-	A	W	F/E	NR, OR	Stroke	7
Handsome II [30]	15	P	F	F/E , A/A, O/R	NR, OR	Stroke, Impaired Mobility	7
RobHand [31]	5	A	F	F/E	NR	Stroke	8
I-PhlEx [32]	1	A	IF	F/E	TR, OR	Injuries	8
Sanchez *et al.* [33]	8	A	F	F/E	NR, TR, OR	Stroke	8
Nobaveh *et al.* [34]	-	P	W	F/E	NR	Stroke	8
Lin *et al.* [35]	1	P	IF, RF, MF, LF	A/A, F/E	-	Stroke	8
Esposito *et al.* [36]	11	A	F	A/A, F/E	NR	Neurological disorders, Stroke	8
Sinfonia [37]	-	A	F	F/E	TR	Neurological disorders	8
Bartalucci *et al.* [38]	1	A	IF	F/E	TR	-	8
Moreno et al. [39]	2	A	F	F/E	NR, OR	Neurological disorders	8
Xiao *et al.* [40]	7	A	H	F/E, S/P	TR	Stroke	7
WIFRE [41]	3	A	IF	F/E , A/A	OR	Stroke	7
Noronha *et al.* [42]	-	A	IF, MF, TF	F/E	OR	Impaired Mobility, Stroke	7
Sanz *et al.* [43]	11	A	F	F/E , A/A	OR	Stroke	7
Serbest *et al.* [44]	1	A	F	F/E	-	Impaired Mobility	8
Asgher *et al.* [45]	5	A	F	F/E	TR, NR	Stroke, Impaired Mobility	8
Shi *et al.* [46]	-	A	F	F/E	OR	Stroke	7

Dai *et al.* [47]	-	A	F	F/E	-	Stroke, Injuries	6
Li *et al.* [48]	2 - 3	A	F	F/E , A/A	TR, OR	Stroke, Neurological disorders	8
Chen *et al.* [49]	-	A	F	F/E	TR, HR	Stroke	7
Secciani *et al.* [50]	1	A	F	A/A, F/E	TR	Impaired Mobility	8
BMIFOCUS [51]	1	A	IF, MF, TF	F/E	TR	-	8
Araujo *et al.* [52]	-	A	F	F/E	TR	Stroke	8
Ma *et al.* [53]	5	A	F	F/E	NR, OR	Stroke	8
Varghese *et al.* [54]	-	A	IF	F/E	-	Impaired Mobility	6
EXOTIC [55]	5	A	H	F/E, S/P, O/C	TR	Impaired Mobility	7
Lu *et al.* [56]	-	P	F	F/E	NR	Stroke	3
PRIDE [57]	1	A	H	F/E	NR, HR	Stroke	8
Sierra *et al.* [58]	-	A	F	F/E	NR	Stroke	6
Meng *et al.* [59]	-	A	F	A/A, F/E	OR	Impaired Mobility	8
Setiawan *et al.* [60]	-	A	IF, MF, RF	F/E	-	Impaired Mobility	8
Liu *et al.* [61]	3	A	F	A/A, F/E	-	Stroke	2
Zhang *et al.* [62]	-	A	IF	F/E	-	Injuries	3
Jaryani *et al.* [63]	-	A	F	F/E	NR, TR	Stroke	6
Heung *et al.* [64]	-	A	IF	F/E	NR, OR	Stroke, Neurological disorders	5
Tang *et al.* [65]	-	P	F	F/E	OR	Stroke, Neurological disorders	6
Stoica *et al.* [66]	-	A	H	-	OR	Stroke, Injuries	3
Liang *et al.* [67]	-	A	F	F/E	TR	Impaired Mobility	6
Den *et al.* [68]	3	A	F	F/E	-	Impaired Mobility	3
Yurkewich *et al.* [69]	-	A	H	F/E , A/A	NR, OR	Stroke, Injuries	7
ExoFinger [70]	2	A	IF	F/E	-	-	7
My-HERO [71]	-	A	F	F/E, A/A	NR, OR	Impaired Mobility, Stroke	7
Birouas *et al.* [72]	-	A	F	F/E	OR	Stroke, Impaired Mobility	6
HandMATE [73]	10	A	F	F/E , A/A	TR, OR	Stroke	7
Yu *et al.* [74]	6	A	F	F/E , A/A	TR	Stroke	7
Takahashi *et al.* [75]	20	P	F	F/E	HR	-	6
Gong *et al.* [76]	-	A	F	F/E	NR	Stroke	6
Erden *et al.* [77]	3	A	IF	F/E	TR	Neurological disorders	6
Lan *et al.* [78]	1	A	F	F/E	-	Stroke	2
A5 [79]	-	A	H	F/E	TR	Stroke	9
HR-06 [80]	-	A	F	A/A, F/E	TR, NR, OR	Injuries	9
Robot Gloves [81]	-	A	F	A/A, F/E	NR	Stroke, Injuries	9
Smart Glove [82]	-	A	H	F/E	TR, OR	Stroke	9
HandyRehab [83]	-	A	F	F/E	TR, NR, OR	-	9
IpsiHand [84]	-	A	F	-	TR	Stroke	9
Hand of Hope [85]	-	A	F	F/E	TR, NR	Stroke	9
MAESTRO [86]	-	A	F	F/E	TR, OR	Bedridden Patients	9
Carbonhand [87]	-	A	TF, MF, RF	F/E	TR	Impaired Mobility	9
EsoGLOVE [88]	-	A	F	F/E	TR, OR	-	9
JAS GL [89]	VAR	P	IF	F/E	-	-	9
InMotion [90]	-	A	H	F/E, A/A, I/E, O/C	TR	Stroke, Neurological disorders	9

Note: Abbreviations: DOF: Degrees of freedom, VAR: Variable DOF, F/E: Flexion/Extension, A/A: Abduction/Adduction, O/R: Opposition/Reinstatement, I/E: Internal/External Rotation, S/P: Supination/Pronation, O/C: Opening/Close, A: Active, P: Passive, Rehab: Rehabilitation, NR: Neurorehabilitation, TR: Telerehabilitation, OR: Occupational Rehabilitation, HR: Haptic Rehabilitation, F: Fingers, TF: Thumb Finger, IF: Index Finger, MF: Middle Finger, RF: Ring Finger, LF: Little Finger, W: Wrist, H: Hand

A. Description

The hand exoskeletons according to their design will present different mechanisms, characteristics, and applications. Allocating them to different parts of the hand, pathologies or types of rehabilitation. Figure 2 presents 4 different hand exoskeleton systems intended for rehabilitation, such as, RobHand [31] which uses EMG-based real-time control and bilateral assisted training, Smart Glove [82] which uses wearable technology and sensors providing tactile and visual feedback, HandMATE [73] which provides at-home rehabilitation and integrates an app that offers personalized exercises and feedback in real-time. and Xiao *et al.* [40] which use a method of real-time recognition of movement intention. According to Table I., 64.06% of the exoskeletons have not been assigned a name. Thus, most are identified by the name of the main author. Therefore, 35.94% of them have trade names or initials. On the other hand, the exoskeleton with the highest DOF number is Takahashi et al. [75]. This device has 20 DOF covering each of the fingers with artificial, pneumatic and light muscles capable of generating contraction forces [75]. Likewise, the most common DOF number in exoskeleton design is 1. In Table 1, the exoskeletons with only 1 DoF represent around 13% and are I-PhlEx [32], Lin et al [35], Bartalucci et al. [38], Serbest et al. [44], Secciani et al. [50], BMIFOCUS [51], PRIDE [57], and Lan et al. [13]. Typically, the goal of having a low DOF number is to reach a functional degree of freedom (fDOF), that is, classifying complex movement patterns in a general way and achieving simpler behavioral strategies [35]. Relating to the type of exoskeleton, we have two classifications: passive and active. In Table 1., 10.94% of the exoskeletons are passive since they generate movement without an external source of energy and they take advantage of the user's own movement, distributing their force and energy, as Tang et al. [65]. While the 89.06% of exoskeletons are active, since they use mechanical components to generate movement, as Jaryani et al. [63]. Likewise, the TLR equal to 8 is the one that is repeated the most, representing in Table 1. 31.25% of the exoskeletons. On the contrary, the TLR equal to 5 represents 7.81%, being the one that is repeated the least.

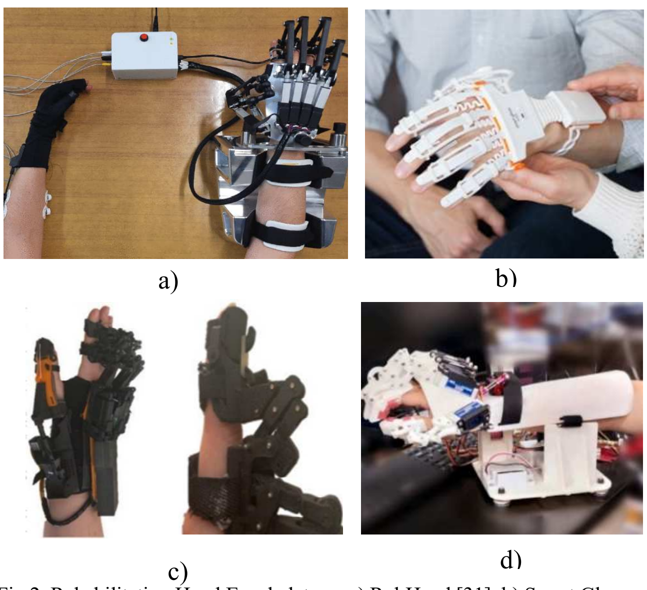

Fig.2. Rehabilitation Hand Exoskeletons. a) RobHand [31]. b) Smart Glove [82]. c) HandMATE [73]. d) Xiao *et al.* [40].

B. Biomechanics

Robotic devices have a biomechanical design that allows the coupling of the device with the hand and its subsequent movement. In this sense, the robotic devices were designed to be installed in the specific part that is sought to be rehabilitated. In the biomechanical design of exoskeletons, most of them are opting for mechanisms that cover the fingers. Since about 97% of the exoskeletons in Table 1 cover at least one finger. On the contrary, the least used mechanism is that of the wrist, with Singh et al. [29] and Nobaveh et al. [34] exoskeletons that are designed solely to mate with this part. On the other hand, the movements that are repeated the most are those of F/E made by almost all the devices. Followed by A/A movements generated mostly by the thumb. This movement is present in 25% of the exoskeletons in Table 1. For example, Handsome II [30], Lin et al. [35] and Esposito et al. [36]. In addition, the design of the exoskeleton does not usually consider movements such as O/R, S/P, I/E and O/C. O/R appearing only 1 time in Table 1. Whereas S/P, I/E and O/C are movements exerted by 2 exoskeletons.

C. Rehabilitation Types

The hand exoskeletons were classified into four categories based on the type of rehabilitation they perform. TR is executed by 45.31% of devices. As Xia et al. [27] that uses tools such as software for human-machine interaction. Exoskeletons such as BMIFOCUS [51] and EXOTIC [55] implement technologies such as VR. Devices such as Moreno et al. [39], Noronha et al. [42], Sanz et al. [43] are classified in the OR, which covers 37.5% of the exoskeletons, exercising techniques such as functional training and repetitive manual tasks. The NR covers 35.94% of the exoskeletons. Generally, they train the hand with bimanual or bilateral exercises, as in Yurkewich et al. [69] and Sanchez et al. [33]. Also in many cases, as in HR-06 [13], they innovate methods such as mirror therapy using the good hand to replicate the movements in the injured hand. The HR represents 4.69% of the devices, including Chen et al. [49], PRIDE [57] and Takahashi et al. [75]. The HR techniques used are haptic rendering to improve the haptic interface for its application in VR. Also, haptic feedback and stimulation are implemented to generate somatosensory sensations.

D. Pathologies

The design of the exoskeletons can be aimed at rehabilitating the effects of one or more pathologies. Mostly, exoskeletons intended for stroke are chosen. This type of exoskeleton represents 62.5% in Table 1, within which are devices such as Shi et al. [46] and Dai et al. [47]. In addition, the impaired mobility classification represents 23.44% of the exoskeletons and includes pathologies such as muscle disorders. Among the exoskeletons dedicated to this classification are Varghese et al. [54], Meng et al. [59] and Setiawan et al. [60]. Likewise, neurological disorders include pathologies such as Hemiparesis/Hemiplegia, spasticity and neuromuscular disorders. They represent around 13% of exoskeletons as Heung et al. [64], Tang et al. [65] and Erden et al. [77]. Furthermore, the classification of injuries includes traumatic hands, spinal cord injury, and other injuries that affect movement. Also, in Table 1 are 10.94% of exoskeletons such as that of Dai et al. [47], Zhang et al. [62] and Stoica et al. [66].

IV. Conclusion

To summarize, this research article offers significant insights into the diverse aspects considered during the development of biorobotic systems as rehabilitation devices. In this review, a total of 64 publications focusing on hand exoskeletons were thoroughly examined and categorized. The articles were classified based on several criteria, including the name of the exoskeleton, the degrees of freedom (DOF) it offers, the type of movement generation mechanism employed, the specific part of the hand it covers, the type of movement it controls, the potential rehabilitation applications, the targeted pathology for treatment, and the Technology Readiness Level (TRL) based on NASA's classification system. It was determined that 64.06% of the exoskeletons do not have a name assigned by their creators. In contrast, the minority of the exoskeletons found receive a trade name or acronym that easily identifies them from others, 35.94% of them being specifically devices such as BMIFOCUS [51], PRIDE [57], among others. While, the exoskeleton Takahashi et al. [75] stands out for having 20 DoF. Being the one with the greatest number of DoFs, covering all fingers with artificial muscles. 1 DoF exoskeletons were also found, such as are I-PhlEx and Serbest et al. [44], which represent 13% of robotic devices. The most widely used DoF number for the design of hand exoskeleton is 1 DoF because fDOF is often used to simplify movement strategies. This review classified the types of exoskeletons into two: passive and active. Most of the exoskeletons are active, being more precise they become 89.06% of Table 1. On the other hand, the passive ones only represent 10.94% of the exoskeletons. Relating to the TLR, for the most part, the exoskeletons are 31.25% of level 8 of the TLR. This article identified that regarding biomechanics, mechanisms that are coupled with the fingers are opted for. Being 97% of exoskeletons capable of covering at least one finger. While the least used mechanism is that of the wrist, whose coupling made only for that part is carried out by Singh et al. [29] and Nobaveh et al. [34]. On the contrary, most exoskeletons are capable of controlling the hand to perform movements such as F/E. Likewise, the second most used movement by the exoskeleton is A/A, which is controlled by 25% of the devices. The review classifies the exoskeleton into four categories based on their application for different types of rehabilitation. The majority can be used in TR sessions, with 45.31% being able to use the tools to execute it, such as Xia et al. [27], BMIFOCUS [51] and EXOTIC [55]. In second place is the OR that represents 37.5% of the exoskeletons. In third place, the NR is controlled by 35.94% of the exoskeletons. Finally, HR represents 4.69% of the devices. In relation to the pathologies to which the exoskeletons are directed, this article pointed out that 62.5% of exoskeletons are designed to treat the consequences of stroke such as Shi *et al.* [46] and Dai *et al.* [47]. Whereas 23.44% of the robots are aimed at impaired mobility. In like manner, 13% represent a design oriented to neurological disorders. Furthermore 10.94% have the design to rehabilitate injuries such as I-PhlEx [32]. The hand exoskeleton improves rehabilitation by providing precise and controlled physical assistance, allowing patients to strengthen the muscles and improve the functionality of the damaged hand, being a versatile and effective tool in rehabilitation.

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